AFRL-ML-TY-TP-2003-4537

RECENT EXPERIENCE USING STEEL STUDS TO CONSTRUCT BLAST RESISTANT WALLS IN REINFORCED CONCRETE BUILDINGS

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Contract No. F08637-98-C-6002

April 2003

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE *(DD-MM-YYYY)*: 20-APR-2003

2. REPORT TYPE: Final Technical Report

3. DATES COVERED *(From - To)*: 01-JAN-2002 -- 15-APR-2003

4. TITLE AND SUBTITLE

Recent Experience Using Steel Studs to Construct Blast Resistant Walls in Reinforced Concrete Buildings

5a. CONTRACT NUMBER: F08637-98-C-6002

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER: 0602102F

5d. PROJECT NUMBER: 4918

5e. TASK NUMBER: C1

5f. WORK UNIT NUMBER: 4918C10B

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S): AFRL/MLQF

11. SPONSOR/MONITOR'S REPORT NUMBER(S): AFRL-ML-TY-TR-2003-4537

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Ref Public Affairs Case # AFRL/MLQ 03-040, 29 April 2003. Document contains color images.

14. ABSTRACT

The design of blast resistant exterior walls for government facilities has become extremely important in recent years due to the increase in terrorist activities worldwide. The design of blast resistant exterior infill walls constructed with steel studs has garnered significant interest within the blast resistant design community. The merits of using steel studs for blast resistant walls include the high strength, stiffness, and ductility of steel, the common availability of steel studs, the ability to construct these walls using common construction tools, and the low skill level required to install the steel stud walls. Recent full-scale laboratory and field experiments have been conducted to understand the blast capacity of the steel stud walls and to validate the design of the anchorage of the steel studs to the concrete structure to develop the tensile membrane capacity of the steel stud wall. This paper will present the results of these laboratory and field experiments. In this paper, an analytical predictive model is used to develop an engineering design methodology.

15. SUBJECT TERMS

steel studs, concrete buildings, blast resistant walls, reinforced

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	9	Robert Dinan
					19b. TELEPHONE NUMBER *(Include area code)*

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Recent Experience using Steel Studs to Construct Blast Resistant Walls in Reinforced Concrete Buildings

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Abstract: The design of blast resistant exterior walls for government facilities has become extremely important in recent years due to the increase in terrorist activities worldwide. The design of blast resistant exterior infill walls constructed with steel studs has garnered significant interest within the blast resistant design community. The merits of using steel studs for blast resistant walls include the high strength, stiffness, and ductility of steel, the common availability of steel studs, the ability to construct these walls using common construction tools, and the low skill level required to install the steel stud walls. Recent full-scale laboratory and field experiments have been conducted to understand the blast capacity of the steel stud walls and to validate the design of the anchorage of the steel studs to the concrete structure to develop the tensile membrane capacity of the steel stud wall. This paper will present the results of these laboratory and field experiments. In this paper, an analytical predictive model is used to develop an engineering design methodology.

Introduction

The recent rise in the incidence of terrorist bombings of high profile buildings has led to increased fervor in the development of a variety of blast resistant construction systems, which may be applied to the exterior walls of buildings. Many commercial buildings today are constructed using reinforced concrete or steel frames with in-fill wall systems. The in-fill systems currently constructed are designed to resist only natural loads such as wind, and to some extent, earthquake loads. For these infill wall systems, the design criterion is specified by a midpoint deflection limit within the elastic response (AISI 1996).

Steel stud members have the desired combination of strength and ductility for blast resistance. The steel stud walls can be constructed as retrofit walls placed inside existing exterior walls, or as exterior infill or curtain walls used in new construction. To design blast-resistant walls using steel studs, it is necessary to ensure a ductile wall performance under large deformations due to blast loads. Ductile performance requires that selected ductile components yield, but continue to carry loads and absorb energy through significant plastic response. Thus, the potential failure modes of the connections must be prevented.

In this paper, the research effort to prevent anchorage failure is presented first followed by the full-scale wall and component static tests to arrive at the static resistance function. The analytical prediction and design method is then briefly summarized. The dynamic field test to validate the analytical model and design procedure is presented followed by a summary and future recommendations.

Anchorage Design

Researchers at the U.S. State Department, U.S. Army Corps of Engineers, U.S. Air Force Research Laboratory, and at the University of Missouri have been collaborating recently to develop a design method to predict the response of fully-anchored steel stud walls exposed to blast loads.

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The original concept for anchoring these steel studs involved cutting the flanges of the steel stud approximately 6" from the end of the stud, and then bending the stud at the web to form a "foot" at the top and bottom of the stud. A hole was then punched in this foot to allow anchor bolting of the stud to the floor and ceiling slab. The bolt holes into the slab were staggered to prevent failure of the slab due to a tension crack joining the holes in the concrete, resulting in failure of the anchoring system, as occurred in an earlier experiment.

This method was used successfully in a full-scale dynamic experiment, EWRP-2 and described in US State Department Technical Information Bulletin (DOS, 2001) and by Wesevich, 2001. However this method does not significantly increase the connection capacity from that of the conventional two-screw method, since the capacity of the connection is limited by the tension required to either fail the stud web in tension (a very localized failure), or failure by the foot pulling over the anchor nut or washer in bearing failure.

Figure 1. Connection detail using clipped flanges and bent at web.

The key to utilizing steel studs in blast resistant systems is designing the steel stud connection so that the connection does not fail but the stud itself fails due to yielding of the steel stud cross section in tension, and eventual failure due to strain elongation limits at the section, which has yielded. The ductile behavior allows for significant energy absorption during plastic elongation of the steel stud, while limiting the reaction forces required at the steel stud connections to the floor and ceiling. The initial study conducted by researchers at the University of Missouri-Columbia, and the U.S. Army Engineer Research and Development Center, ERDC focused on the development of an anchoring system to attach the steel stud to floor or ceiling slab in order to develop the full tensile capacity of the cross section of the steel stud (Muller 2002). Conventional steel stud anchoring consists of attachment of the steel stud to a steel track using two (or in some cases, four) self-tapping screws. These screw connections are insufficient in developing the full tension capacity of the steel studs (Roth 2002). The approach to designing the required anchorage involved static analyses and laboratory testing so that the connection capacity exceeds the tensile yield capacity of the stud.

The concept chosen for development uses a steel angle slightly narrower than the web width of the stud, with the vertical leg of the angle attached to the web of the stud, and an anchor bolt through a pass hole in the horizontal leg of the angle anchored into the floor and ceiling. This angled connection was designed to prevent connection failure in a variety of modes:

- Shear Failure of the Angle to Stud Connecting Bolts
- Tension failure of the Angle in Cross-Section
- Block Shear between Bolt Holes in Steel Stud
- Bearing failure in Steel stud directly below bolt holes

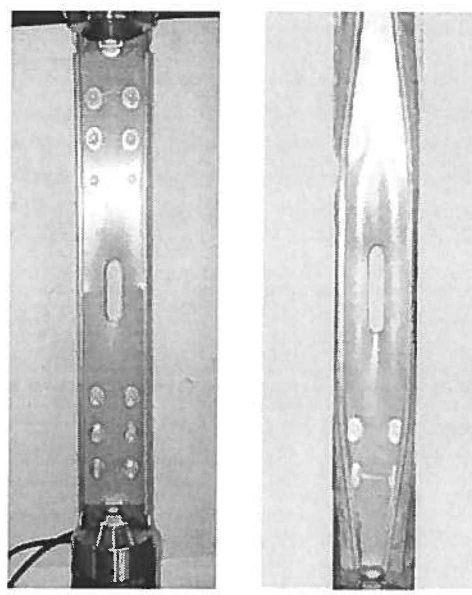


Figure 2. Steel Stud Specimen Loaded in tension; note six bolts were required to yield the steel stud cross-section

Static tension experiments were conducted to verify the number and size of bolts required at the connection of the angle to the studs (Shull 2002). Calculations determined that six bolts were required to cause the steel stud to yield in cross-section, as shown in Figure 2.

The next objective was to determine the required combination of anchor washers or material thickness of the angle connector to prevent pullover of the anchor bolt that will be used to attach the steel angle to the concrete floor or ceiling slab. This was determined experimentally using a tension-loading machine with various combinations of angle steel thicknesses, washer sizes and thicknesses. The loading geometry for these experiments provided a more extreme loading condition than the actual blast loaded stud wall, but this experimental method would provide a conservative design. After several iterations of these parameters, ½"-thick steel angle was chosen as the best candidate to prevent pullover of the anchor bolt as shown in Figure 3. The anchor bolt connection into the slab was designed according to the CCD anchor design methodology as described in the ACI 318-02, Appendix D (2002) using appropriate factors for anchor spacing and edge effects.

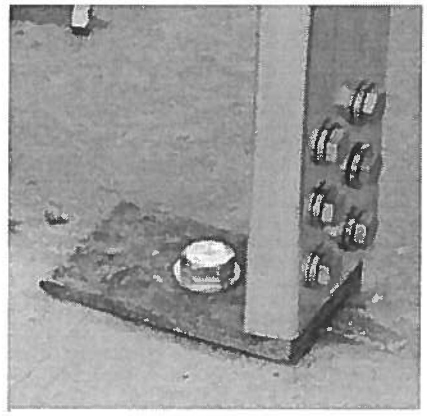


Figure 3. Stud-to-Floor Anchorage using a ½"-thick Steel Angle

Once the connection details were determined and tested, the next step was to determine the load versus deflection response of a transversely loaded steel stud wall, which can be used for dynamic modeling. One approach involved loading the stud or a stud pair via a "loading tree" that distributed the load from hydraulic actuators to sixteen equally spaced points on the stud. The static experimental program to develop the resistance function is summarized next.

Static Resistance Function

To be able to conduct dynamic modeling and arrive at engineering design tools for blast loads, it is necessary to first develop the load-deflection response of the wall under uniform pressure: static resistance function. The performance of the steel stud wall depends, among other things, on the response of the individual stud components that make-up the wall. The elastic, as well as the plastic response of the steel studs to failure is obtained through static full-scale component and wall tests. The experimental set-up described here is for blast-retrofit wall systems, in which the connections are sufficiently designed to ensure failure in the studs, as discussed in the previous section.

The component tests are conducted by loading a stud or a stud pair via a "loading tree" that distributed the load from hydraulic actuators to sixteen equally spaced points on the stud (Figure 4). Note the wooden blocks used as bearing stiffeners at the loading points to prevent local buckling, and the vertical steel guides which prevented torsional buckling of the section. The load and deflection response to failure is recorded, and equilibrium is then used to calculate an "equivalent" pressure per unit width. Another device that was used to obtain a static resistance function on a full-scale wall section is the static uniform resistance chamber located and operated by the University of Missouri–Columbia. This device is capable of applying a uniform load to a 12' by 10' wall section using a vacuum pump (Figure 5). A typical response of a steel stud component test and a wall test are shown in Figure 6.

The analytical model shown in Figure 6 is divided into three regions: Linear elastic (Yu 2000); post buckling softening; tension membrane. From experiments, it is observed that in some instances the studs experience a "softening" region after yield-buckling and before going into the tension membrane region. For example, the stud shown in Figure 6 experienced a softening region. In other instances, the studs could go into tension membrane right after the yield-buckling is achieved (as will be seen later). The shape of buckling at the stud mid-span might control such responses. Therefore, the analytical predictions are developed to give a "low-end (LE)" and a "high-end (HE)" resistance function to completely represent both possible behaviors.

In the following section, the analytical/experimental model is used to design two stud wall systems and to verify the response using explosive field testing.

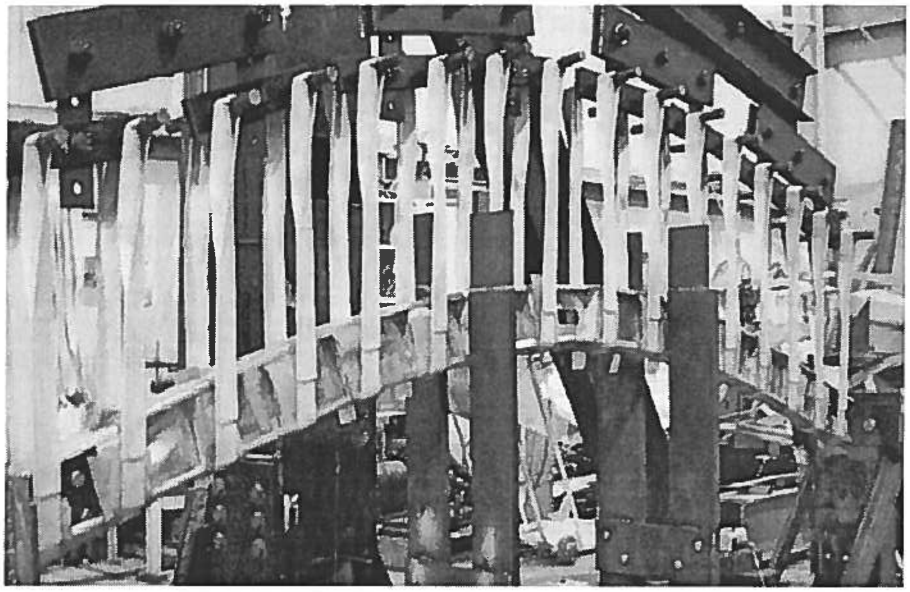


Figure 4. Loading Tree Component Test Set-Up

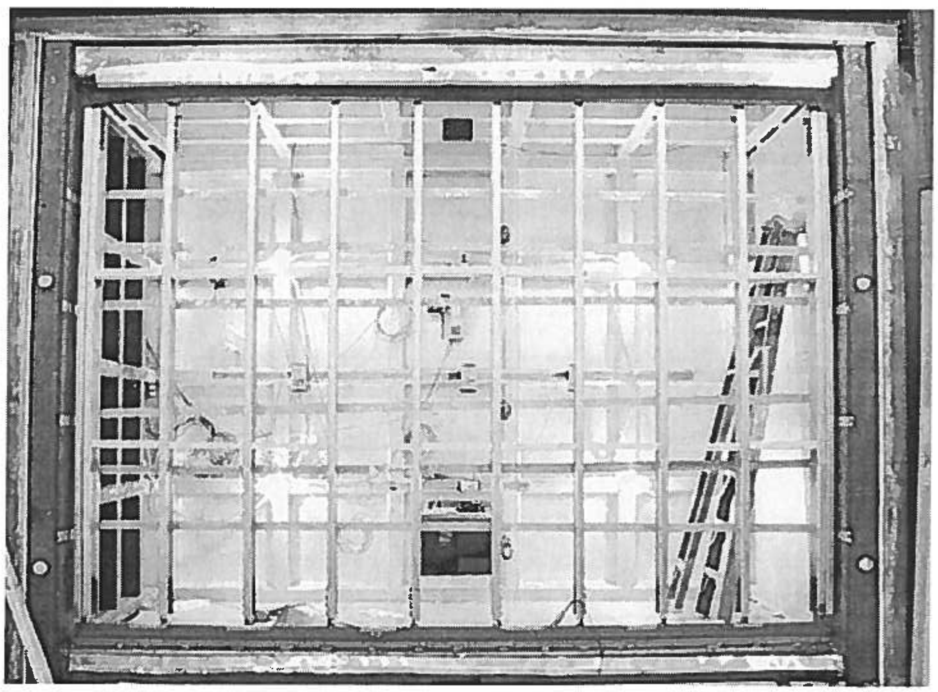


Figure 5. Typical Stud Wall Test Set-Up

Full-Scale Dynamic Experiment

The results of the static experiments were used to develop a resistance function defining the uniform load versus deflection behavior of the steel studs as discussed in the previous section. The resistance function for the steel studs used in the dynamic field test is shown in Figure 7.

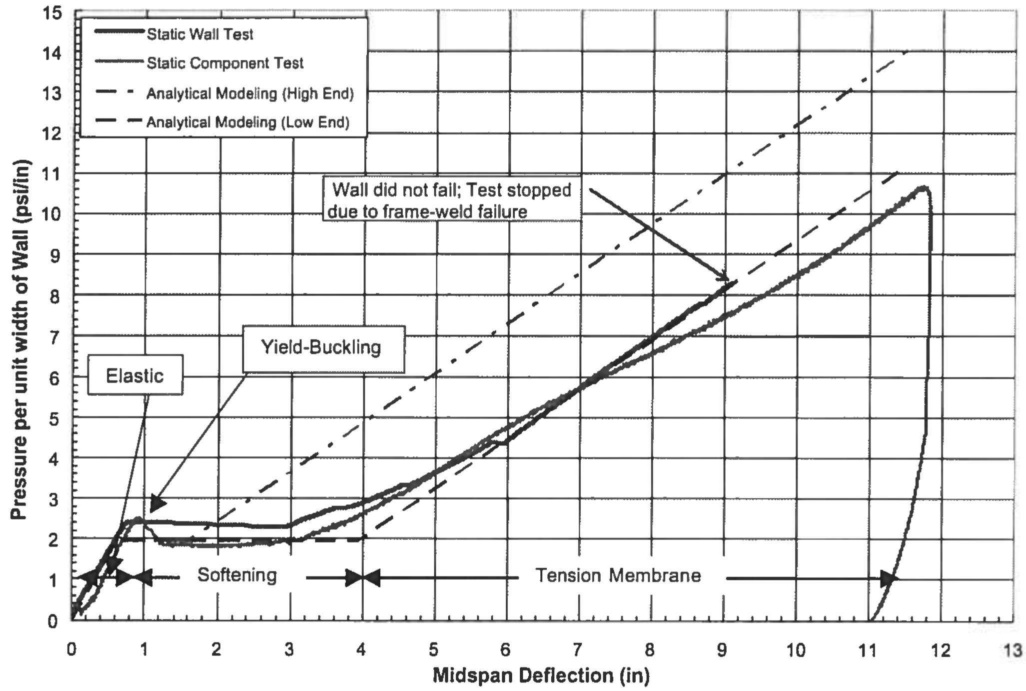


Figure 6. Typical Static Resistance Function of Steel Stud Wall and Component System

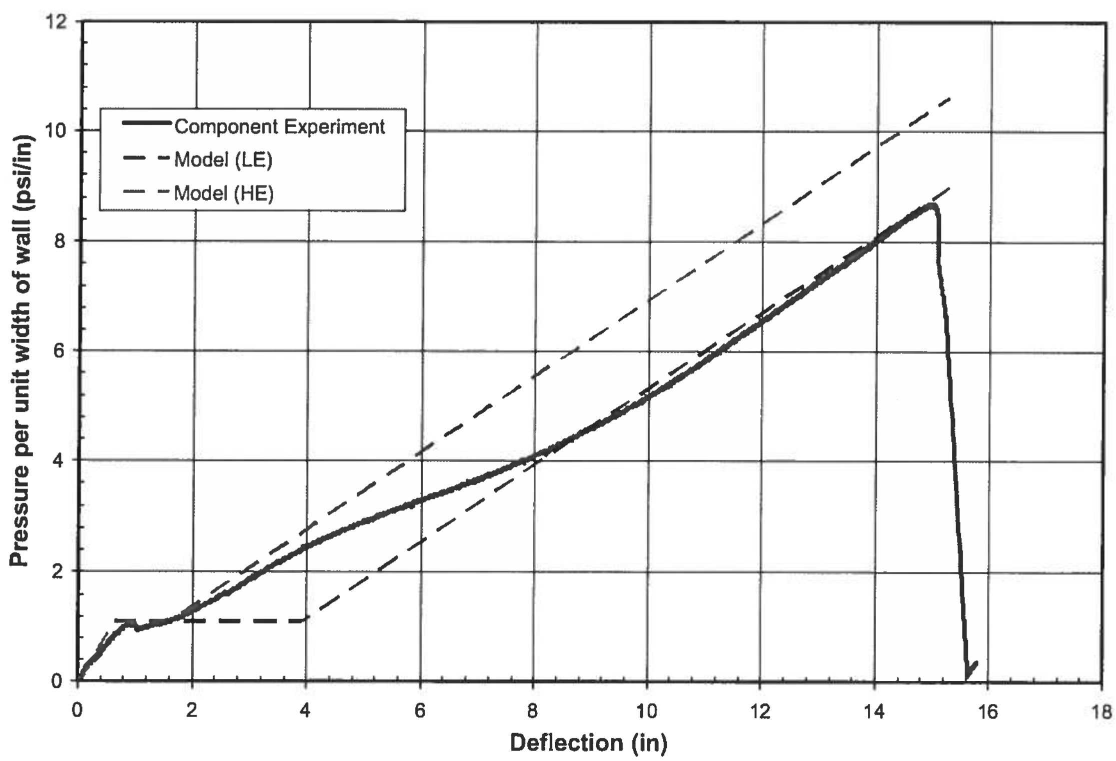


Figure 7. Static Resistance Function for Steel Stud used in the Dynamic Field Tests

This resistance function was then used in a single degree of freedom model to predict the behavior of the wall system when subjected to blast loads. As part of the Blast Response of Exterior Walls (BREW) research program, a full-scale blast experiment (BREW-1) was conducted at the Air Force Research Laboratory range at Tyndall AFB. The purpose of the experiment was to validate the performance of the anchor systems in developing the full tensile capacity of the studs, to demonstrate the contribution of the mass to the wall response, and to compare the results of the experimental data to the preliminary model. Two steel stud walls with blast-design connections were tested. The steel stud walls consisted of 600S162-43 studs (AISI 1996), with a specified yield strength of 33ksi, with single studs spaced 16" apart. The walls were approximately 144" tall, and were attached at the bottom to a reinforced concrete slab using concrete anchors, and at the top to a steel plate (representing either a steel beam, or an embedded steel plate in concrete) using a steel angle welded to the plate, and a hole in the vertical leg of the angle to allow for a hinged connection (Figure 8). One wall contained a brick façade consisting of 7-9/16" Wide x 2-3/16" Tall x 3-1/2" Deep clay bricks with an area density of 30.5 lb/ft^2. The façade of the other steel stud wall consisted of a typical External Insulation and Finish System (EIFS) exterior with an area density of approximately 1.5 lb/ft^2. The exterior side of the studs was sheathed with 16-gauge sheet steel, and the interior studs were sheathed with a product consisting of ¼" gypsum board glued to 20 gauge steel sheets to provide a finished interior surface while preventing secondary fragmentation from the gypsum board (Figure 9).

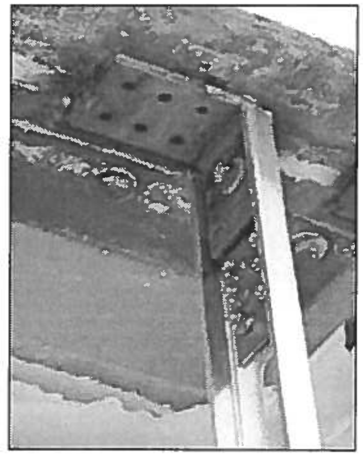
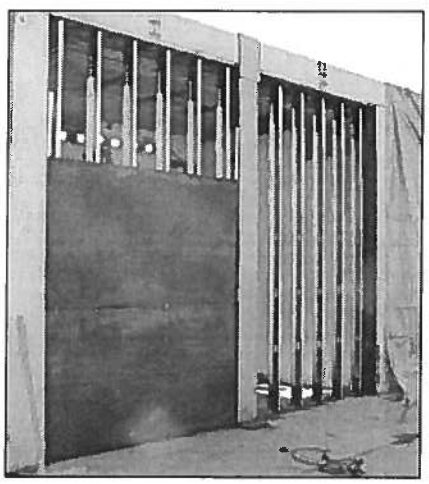


Figure 8. Connection Detail at Top of Stud Showing Attachment to Embedded Steel Plate



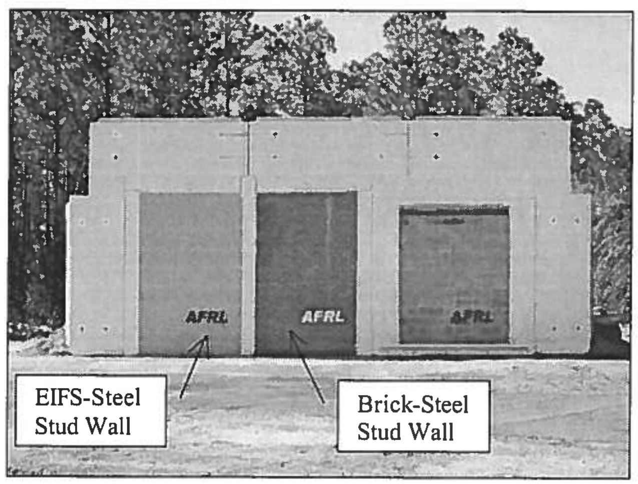


Figure 9. Pretest Exterior Photo of BREW-1 Structure Showing EIFS and Brick Façade on Steel Stud Walls Anchored using Blast-Resistant Connection Design; Walls During Construction (left)

The walls were subjected to a blast loading with 33-psi peak reflected pressure and 200 psi-msec peak reflected impulse as shown in Figure 10. The post-test photos shown in Figure 11 and the deflection measurements shown in Figure 12 demonstrate the dramatic difference in wall response resulting from the inertial effects of the mass of the wall. The deflection measurement at the center of the steel stud wall with the brick façade indicated a peak inward deflection of 6.8 inches, with a residual deflection of 5.2 inches. The preliminary model predicted that the wall would survive and predicted a peak center deflection of approximately 11 inches. Note that the current model considers only the mass of the façade, and does not yet include any increased resistance provided by the bricks. The deflection measurement at the center of the steel stud wall with the EIFS façade measured the

gage maximum of 32 inches inward deflection, and gave no indication of when the steel st .d wall failed. The steel studs that failed on the EIFS wall during testing were eased back into place during post-test forensics in order to estimate the plastic deflected shape when stud failure occurred. The average peak mid-span plastic deflection that occurred at stud failure was measured to be approximately 14 inches. This compares well to the EIFS-steel stud model that predicted stud failure at approximately 18 inches (plastic plus elastic) deflection, although the theoretical response is somewhat softer than experiment.

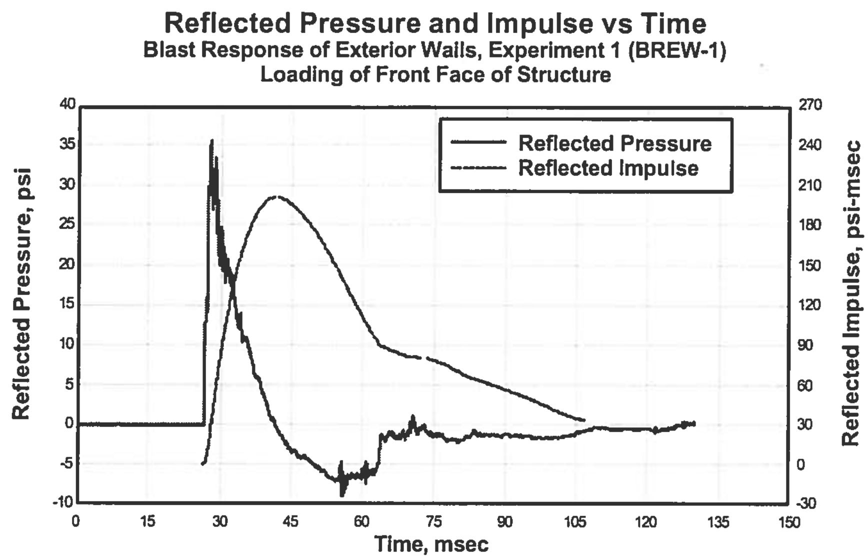


Figure 10. Reflected Pressure and Impulse Waveforms Measured of Wall Surface for BREW-1 Experiment.

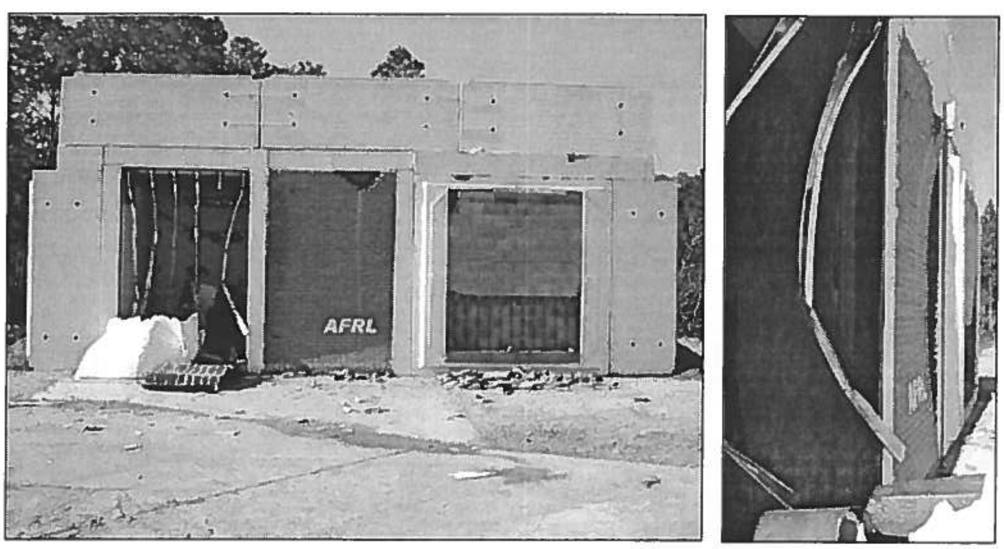


Figure 11. Post Test Exterior Views of BREW-1 Structure Showing Large Deformation and Failure of Low-mass EIFS Façade and Response of Higher Mass Brick Façade.

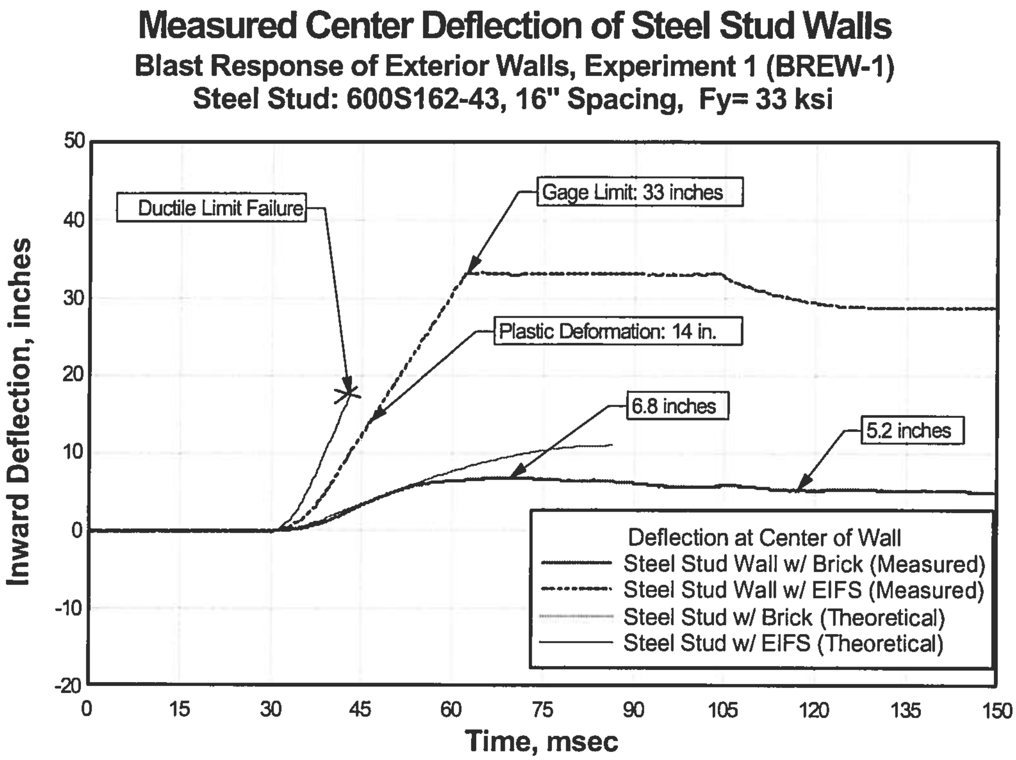


Figure 12. Measured and Predicted Deflections at center of Steel Stud Walls for BREW-1 Experiment.

Conclusions

Properly anchored steel stud walls have proven to be an effective solution for construction of blast resistant walls for either new or retrofit construction. Some research has been performed to date to develop design methodologies for the required connection details, and to understand plastic post-buckling behavior and strain limits of the steel studs. The connection design has proven to be very successful at developing the yield capacity of the stud, forcing a ductile failure in the stud. The effectiveness of mass at reducing the response of the wall to blast loadings is dramatically demonstrated in the experiment and in the model. The theoretical resistance functions and preliminary model provide a somewhat conservative prediction of the steel stud wall response, allowing engineers to design a blast resistant steel stud wall that will survive a given explosive threat.

Acknowledgements

The authors gratefully acknowledge the diligent efforts, generous funding and encouragement of the members of this research team comprised of several agencies including the U.S. Army Engineer Research and Development Center, (Dr. Beverly DiPaolo and Dr. Stan Woodson) the US Department of State (Mr. Wayne Ashberry, Mr. Donald Moffett, Mr. Russ Norris, Dr. Ali Amini), the University of Missouri-Columbia (Dr. Sam Kiger, Mr. John Shull, Mr. Jeremy Roth, and Mr. Paul Mueller), Center for Cold-Formed Steel Structures, University of Missouri-Rolla (Dr. Roger LaBoube), and The US Army Corps of Engineers Protective Design Center (Mr. Patrick Lindsey).

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